TECHNOLOGIES FOR DEVELOPMENT OF MORE AFFORDABLE LARGE X-RAY SIMULATORS

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Abstract

Pulsed power conditioning elements between the energy-storing capacitor banks and the radiation loads have been the major cost driver for large simulators [1]. The cost is driven by the pulsed power requirements needed to provide the necessary spectral and temporal characteristics of the radiation output for Nuclear Weapons Effects Testing (NWET), as well as for assuring efficient production of the radiation. During the past forty years, the Defense Threat Reduction Agency (DTRA) has developed pulsed power elements and systems that are lowering the cost of x-ray simulators. This paper discusses these technologies.

I. INTRODUCTION

Elimination of underground testing in 1992 has placed increased emphasis on x-ray simulators to provide adequate means for nuclear weapons effects testing. The need for increased simulator capability points to an increase in the simulator current by an order of magnitude, to an ultimate level of 100 MA for a plasma radiation source (PRS). This involves capital expenditures which must be kept at an affordable level. A forty-year period of pulsed power development has seen improvements in components leading to increased power flow performance, as well as in better understanding of the radiation load physics. With the maturation of simulator pulsed power technology, significant steps can now be envisioned toward reducing costs of new simulators. Fig. 1 portrays the DTRA simulator development program which builds on innovations in pulsed power technology, through a series of simulators, toward an affordable full-capability simulator which would rely on parallel advances in load physics.

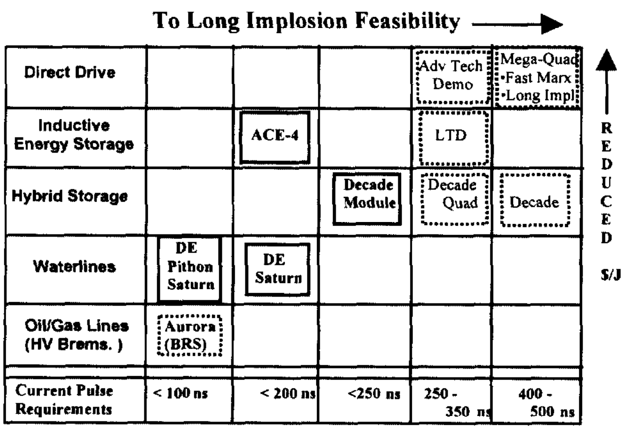

Figure 1. Simulator technology development is moving up toward lower cost facilities for plasma radiation sources.

The significance of the advances in pulsed power can be assessed by examining the basic water pulseline technology for power conditioning, the energy stored in capacitors and released in a multi-staged Marx circuit. The energy is transferred to a waterline or water capacitor, with perhaps more than one stage of these waterlines, through low-inductance switches, resulting in ever-decreasing pulse-width, providing a large increase in the output power. Because the bulk of the cost (up to 85% of the total cost) to build such a system is in the power conditioning stages, it is important to reduce this portion of the simulator [2].

The DTRA generators shown in Fig. 1, incorporate many new energy storage and power flow techniques. Advances were made in all elements of the power flow chain and include significant improvements in coupling of the power to the load through better understanding of the load physics. Advances in pulsed power conditioning, inductive energy storage (IES) and plasma opening switches (POS), and in load physics were important factors in the decision to proceed with the next simulator, the Decade-Quad [2,3].

Fig. 2 attempts to quantify the cost of various systems normalized by the capacitor bank energy. The energy density generally increases and the cost decreases as the use of waterlines is reduced through IES and POS technology. More recent understanding of the opening switch technology and load physics suggests that capacitor banks connected as fast Marxes or as linear transformer devices (LTD) [4] driving POS (or loads,

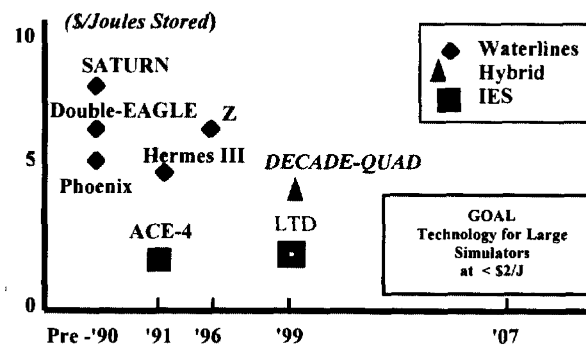

Figure 2. Simulator cost per stored energy has decreased with advanced technology developments.

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14. ABSTRACT **Pulsed power conditioning elements between the energy-storing capacitor banks and the radiation loads have been the major cost driver for large simulators [I]. The cost is driven by the pulsed power requirements needed to provide the necessary spectral and temporal characteristics of the radiation output for Nuclear Weapons Effects Testing (NWET), as well as for assuring efficient production of the radiation. During the past forty years, the Defense Threat Reduction Agency (DTRA) has developed pulsed power elements and systems that are lowering the cost of x-ray simulators. This paper discusses these technologies.**					
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directly) can reduce the size and cost of simulators to the less than \$2/J-stored level.

The innovations occurring in pulsed power starting with the 1960's had a significant impact on simulator technology. Very early simulators like Aurora were designed around oil blumleins and were very large. However, in the late '60's, new systems with names like Gamble, Blackjack, Owl and Speed appeared; these systems used transmission lines with water dielectric replacing gas and oil as the insulating dielectric. These systems also required the development of low-inductance closing switches, both for the fast Marxes as well as for waterline stages.

As these systems were being built up from 1 to 10 terawatts (TW), much of the R&D was dedicated to diode physics, beam transport and pinching, and plasma radiating sources. By the late '70's, there was an impressive suite of simulators in the country able to produce various portions of the x-ray spectrum to develop radiation-tolerant electronics and optical elements in support of the underground testing (UGT) program.

In the mid-'80's, DTRA decided to develop IES technology as a path to more affordable systems, with energies greater than the DOE Saturn 20-TW system [3]. Storing the energy inductively requires a conducting element which must open at peak current time and transfer the energy efficiently to a, typically, one-ohm diode load. In applications to DTRA simulators, the development of a switch with low resistance in a closed state and which could open in less then 100 nanoseconds to several ohms, was required. Cliff Mendel at Sandia National Laboratories (SNL), had demonstrated that a low-density plasma in the vacuum power flow line could conduct during the early current pulse and steepen the power rise time by a factor of two. This initiated the development of the POS, which appeared to be the solution to the IES technology for simulators. This technology led to systems like Decade, ACE and Hawk where the POS development has been done for DTRA. Significant effort continues to be expanded in this area, as evidenced by the articles on this subject contained in these Proceedings.

The '80 and '90 decades are characterized by the significant R&D effort relying on increased stressing of all components to increase the energy efficiency and thus reduce costs. The development in the last three years, critical to DTRA programs, is the study of x-ray production techniques using the radiating plasmas driven over long implosion times (>100 ns) to generate high yields of soft x-rays. Establishing the feasibility of long implosions to produce x-rays will reduce the need for power conditioning, leading to the reduction of the cost of future systems.

II. MILESTONES AND TRENDS

Descriptions follow of some of the advances made with the elements of pulsed power which impact the development of affordable future simulators.

A. Capacitors

Early development of the capacitor component for large pulsed power systems was supported by DOE large fusion devices. The 5-MJ "Scyllac" theta pinch built at LANL in the 1970's required advanced capacitors. The Scyllac capacitor at 50 kJ/m^3 became the standard of the μs discharge capacitor, and DTRA continued the development to 80 kJ/m^3 and built Marx capacitor banks for the early x-ray simulators named MBS, Blackjack, Owl, Gamble, Casino, Pithon, Double-EAGLE, Phoenix, and Aurora. The latest simulators supporting DTRA programs are known as Hawk, ACE and Decade and are using a slightly more advanced "Fastcap" type capacitors up to 170 kJ/m^3 [5]. SNL has built fast pulsed power systems like Speed, Proto, Saturn, Hermes, and Z using similar fast capacitors.

There has also been interest in developing higher energy density capacitors for other military applications that could use ms discharge times. Energy densities up to 2.7 MJ/m^3 have been manufactured for this application.

Fig. 3 shows benchmarks of the capacitor technology developments.

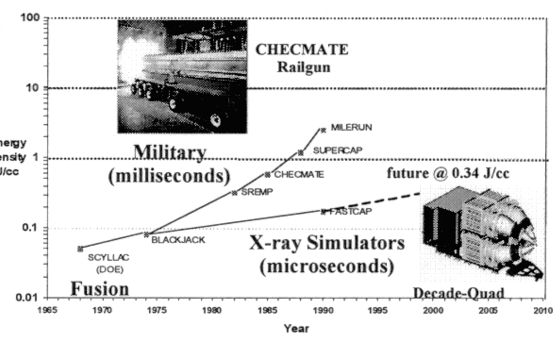

Figure 3. The development of high energy density capacitors has progressed along two different requirement paths.

There are also new higher energy density materials being developed which, with low inductance designs, suggest that sub-microsecond capacitors could be developed with a factor of two in the energy densities [6]. This could support high-voltage Marx circuits with a few megavolt outputs and <0.5 μs quarter period time.

B. Closing Switches

Radiation simulators utilize two types of closing switches: pressurized gaps at 10's of kV for the Marx capacitor banks and oil, gas, or water switches in the power conditioning stages for the MV levels. Both types must have low inductance so that the advantage of staging is not lost or degraded. Pressurized spark gaps were developed very early and were used in the late '60's on the Aurora system. The triggered multi-channel rail switch was a low inductance version of the pressure switch being used in the ACE-4 facility and in the developing LANL Atlas system. Recently, a design to double the discharge channels and use low-damage graphite electrodes was developed [7], and a French-Russian collaboration has developed a switch based on a concept where a low inductance array of steel balls form multiple gaps for fast switching of capacitors [8].

C. Water Pulselines

In the early 1960's, J. C. Martin developed water breakdown scaling laws [9] which led to many new generators using water as a dielectric. Studies in the 1970's showed that it is practical to operate at 100%-110% above breakdown for x-ray simulators because the breakdown channels are high impedance and energy is drained off into the load without damaging the pulse-lines [10].

Other studies of enhancing the energy density of water dielectrics, such as pressurized water [11], introduction of conducting layers [12] and admixtures of different dielectrics [13] as insulators for high power generators, have not led to practical results.

Cost associated with the water pulselines and complex power flow sections for providing high power density at the output motivated DTRA to develop simulator systems minimizing use of water (Decade), or systems without waterline sections (ACE-4). Far-term plans (Fig. 1) envision future systems employing very fast Marxes or Linear Transformer Devices (LTD) to drive the PRS loads directly.

D. Vacuum Interface

The stacked insulator interface between the waterline and the vacuum diode continues to improve over the years. Early experience with polyurethane, machined from molded cylinders, had limited lifetime to surface damage from hot converter package debris as well as from electrical effects of dendrites, worm-holing, and bulk breakdown. Development of a surface plastic layer, Limitrac, developed by Westinghouse, made improvements in the surface damage and extended the lifetimes. However, this material was brittle and created some new challenges. A more recent study completed by MPI has shown a surface coating called Dendresist to be a superior coating, and some changes in the cross-section of the insulators can reduce the bulk breakdown and worm-holing [14]. Insulators fabricated according to these formulas are being tested on Double-EAGLE as shown in Fig. 4 during their installation.

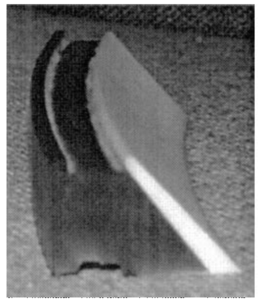


Figure 4. Cross section of an earlier insulator design and a new set of rings being installed in DoubleEAGLE.

SNL is also revisiting the flashover criteria for the vacuum insulator surfaces. Recent measurements at SNL have shown that magnetic insulation of the vacuum-insulator stack is occurring in the triple-point on the Z accelerator. This effect plays a large role in improving z-pinch outputs and may be a large factor in design of future z-pinch drivers [15]. This is supported by an observation that the insulator stack in the Z accelerator performs better than predicted by the JCM flashover criteria [16]. In large-scale tests on Z, an increase of 50% in the stress across an insulator (tested without the load) was obtained [15]. This reduces critical inductance at the load, that should lead to more efficient transfer of power to the load in systems such as DE (in Fig. 1) or Z. It is for this reason that the interface materials such as Rexolite are being tested for operation at 200 kV/cm stress [17].

E. Plasma Opening Switches

With the advent of the Decade simulator, preceded by the DM 1 and 2 modules (Fig. 1) designed as a hybrid system, the POS was demonstrated to be a key to increasing power density of the modular machines [1]. In this application, the POS eliminates the need for vacuum interface in the load area and replaces a conventional power conditioning stage. The decision to use POS in the Decade program led to extended studies which resulted in advancing the opening switch technology. The range of parameters over which POS was shown to operate as a power conditioning element was extended significantly. It was shown to have a very small jitter time, e.g., measured on a Decade-Module to be 6 to 7 ns for a conduction time over 300 ns, making modular pulser designs possible [18].

More recently, scaling between the conduction time and current was established [19]. The present levels of POS switching (3.5 MA, 1-1.5 MV at the ACE-4 testbed [20]) shown in Fig. 5, together with the scaling, provide confidence in the design of simulators for the high implosion velocity PRS operations. The fast implosion

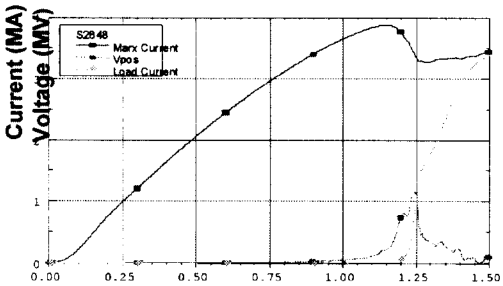

Figure 5. ACE 4 current and voltage into an inductive load showing full transfer of the POS current in 30 ns.

velocities are believed to be necessary for the production of radiation with a large component of high-energy photons. Development of the single monolithic POS for switching a combined current from several modules (Decade-Quad) would provide an option to drive a single BRS diode as well as the high velocity implosions. Further studies of the POS may improve the efficiency by up to 25% by reducing ion losses; for example, through heating of the anode and cathode surfaces of the POS [21].

SNL is developing a triggered version of the POS, based on the magnetically controlled POS (MCPOS) that provides an alternative to the POS in simulator designs [22].

F. Vacuum Power Flow

There have been significant advances in the detailed designs for vacuum power flow, and the process has been accelerating with the use of 3-D codes [23]. Of particular interest has been the power flow associated with the vacuum post-hole convolutes since they form a magnetic null that can lead to current loss. Even without the magnetic nulls, there are conditions in which the electrons separate from the conducting metal in the magnetically insulated transmission lines (MITL), and special design features are used to minimize this effect.

III. INTEGRATION WITH LOAD PHYSICS

Another productive approach to the reduction of simulator stages and components is the development of radiation loads that can be driven with longer output pulses.

A. Plasma Radiation Source Loads

Recently, significant progress has been made in extending the implosion time of the PRS loads, eliminating the need of some power conditioning stages. This is reflected in Fig. 6, which summarizes the scaling

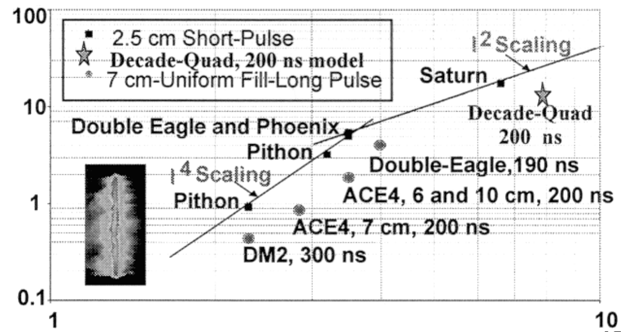

Figure 6. Argon k-shell yield (kJ/cm) versus the peak z-pinch current (MA).

experiments and corresponding modeling of the radiation output, projecting the expected performance of the Decade Quad. These results indicate that DQ can operate without the opening switch for PRS loads using a convolute to collect the current from all four modules, providing about 8 MA into a single load.

The development of the Plasma Radiation Source (PRS) has seen significant advances in the past couple of years that will allow us to develop lower-cost simulators that don't require as much power conditioning. Fig. 6 shows the argon K-line yield per length of the pinch for several different simulators. Data designated by squares is for implosion times less than 100 ns. The physics of the radiating plasmas suggest that the K-line yield goes as the current to the fourth-power up until it becomes efficient in radiating the energy, and then scales as the current to the second-power. Saturn provides enough current to the argon load to operate in this efficient region.

In the early experiments, using the Decade-Module at 300 ns implosion times without the POS and ACE-4 at 200 ns implosion times with the POS, yields were generally a factor of two below the "expected" yields from the same peak current with the fast implosions. Later, Double-EAGLE and Saturn were converted for longer diode power pulses, 190 ns and 180 ns, respectively. Preliminary results suggest that the Decade-Quad should work well with the initial operating condition using the direct drive approach with the 300 ns output power pulse. The modeling suggest that around 12 kJ/cm of argon K-line radiation could be produced with the 200 ns implosion as indicated in Fig. 6.

B. Bremsstrahlung Source Loads

The early e-beam and high-voltage bremsstrahlung simulators, such as Aurora, were limited in current according to the Child-Langmuir (C-L) law due to the electron space charge in the diode gap. When the power conditioning technology switched to the waterlines to increase the output current for given voltages, a large voltage pre-pulse was introduced into the diode due to the high capacitive coupling between stages. This led to higher current, lower impedance diodes because they operated, in effect, as plasma-filled diodes (with currents exceeding the C-L limit by large factors). Now, there are no generators with large pre-pulses. The high currents are obtained by using pinched diodes, that scale as R/d. This also allows the operation of ring diodes which produce e-beams using parallel concentric pairs of cathodes. Saturn derived its name from the ring cathode structures.

The series diode was developed to reduce the end point energy of the electrons by the number of diodes in series. Two- and three-series diodes have been successfully demonstrated on DoubleEAGLE. [24]. Reflex diodes and triodes have also been successfully developed on DE where the bremsstrahlung converter is very thin and the electrons are allowed to reflex several times through the foils [25]. This produces a much lower average energy x-ray spectrum. Fig. 7 shows a schematic drawing of a reflex diode.

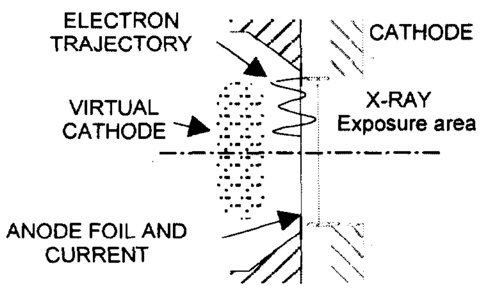

Figure 7. A schematic drawing showing the concept of a reflex diode.

Plasma-filled diodes using externally injected plasma may find a role in low-voltage bremsstrahlung radiation sources (BRS), or in improving the performance of the POS-driven diodes. Rod cathodes are another possibility and have been applied in radiography sources [26]. Transporting the e-beam to converge the power on a smaller areas is being studied to determine whether injection and transport to BRS targets from multiple modules can operate efficiently at the high power density needed for some simulator applications.

This method of converging the diode energy is being also explored as part of the planning for even higher power densities in Decade-Quad; both gradient drift [27] and plasma channels [28] appear to be feasible approaches.

V. CONCLUSION

Over the nearly forty years of developing pulse power for x-ray simulators, DTRA has moved from very large oil-lines in Aurora through the waterlines of DE (also utilized in the Saturn and Z facilities) and into the inductive energy storage POS systems like DM, DQ, and ACE-4. Simultaneously, DTRA has developed more efficient performance for both the bremsstrahlung and plasma radiation source diodes. In parallel with the component technology, pulsed power generator designs also have evolved. Introduction of water as the dielectric led to the development of pulsers with multi-megampere output substantially above the level that was practical with the gas or oil dielectrics. For waterlines to work efficiently with short duration output, pulsers' water sections required multichannel switching (with synchronization for modular designs). Distributed pulseline transformers were also employed that allowed increases in the current output while maintaining the risetime [29].

At the same time, POS has been developed to operate with long charging times, >1 μs, directly from a Marx capacitor bank. The most recent results are reported in these proceedings [30].

Concept studies of the future simulators also include un-switched (passive) waterline decouplers as part of the simulator. Increasing the energy density of large water pulselines through higher electrical breakdown stresses in water has been the subject of many studies [31]. The possibility of eliminating all waterline elements has also stimulated the development of ultrafast Marxes [32] and LTD systems [4]. Combining the pulsed power technology innovations with new data and better understanding of the implosion physics is likely to lower the cost of large pulsed power systems to <$2/J of stored energy. Innovations with both the capacitors and load designs will be required. This will also provide added versatility for radiation testing, as in the case of the Decade simulator where both hot (bremsstrahlung) and cold x-rays will be available.

It now seems possible to complete the process by developing faster capacitor Marx circuits which can be coupled directly to the new imploding load configurations.

VI. ACKNOWLEDGEMENT

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